AUTOCORRELATION AND CROSS-CORRELARION ANALYSES OF ALPHA WAVES IN RELATION TO SUBJECTIVE PREFERENCE OF A FLICKERING LIGHT

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Abstract-**To clarify the relationship between the human brain activity and subjective preference of a flickering light under changing temporal frequency and mean luminance, alpha waves were analyzed by autocorrelation function (ACF) and cross-correlation function (CCF). Paired-comparison tests were performed to examine the subjective preference of a flickering light. Electroencephalograms (EEGs) were recorded from 7 electrodes (10-20 system) during presentations of the most preferred and the least preferred flickering-light conditions. From the initial delay range of the ACF, the effective duration (τ_e) was determined to describe the temporal characteristics of the alpha waves. Results show that the preferred flickering light has a significant larger τ_e than that of the least preferred flickering light especially at the occipital area. In addition, the maximum value of the CCF ($|\phi(\tau)|_{max}$) between the alpha waves and its delay time were analyzed. Results show that the preferred flickering light has a significant larger $|\phi(\tau)|_{max}$ than that of the least preferred flickering light.**
Keywords - **Alpha waves, Autocorrelation function, Cross-correlation function, Subjective preference**

I. INTRODUCTION

In discussing the brain activities in relation to the human's behavioral states, Lindsley reported that an electroencephalogram (EEG) corresponds well to alpha waves, which are always produced in relaxed states and are associated with free creative thought [1]. The differentiation of basic emotions, i.e., intention, anxiety, aggression, sadness, and joy, by means of EEG-coherences has been discussed extensively [2]. Concerning the relationship between brain activities and subjective preferences as an overall impression of a sound field, Ando and Chen and Chen and Ando developed a method of using the autocorrelation function (ACF) to analyze brain waves [3-4]. They analyzed the effective duration of the envelope of the normalized ACF (τ_e) of the alpha waves when temporal factors were changed. Their results showed that τ_e of the alpha waves is longer only in the left cerebral hemisphere for the preferred conditions of these temporal factors. In addition, Chen, Ryugo, and Ando showed that τ_e of the alpha waves is longer only in the left cerebral hemisphere for the preferred tempo of noise burst [5].

Accordingly, it is quite natural to assume that subjective preference of visual stimuli is reflected in the human brain activity and physiological responses. The purpose of this study is to examine whether or not subjective preference of visual stimuli reflects the temporal information in brain waves on the left and right cerebral hemispheres. At first, paired-comparison tests were performed to examine the subjective preference of human subjects for light sources of changing temporal frequency and mean luminance. From the results of the scale value of subjective preference, the most preferred and the least preferred light sources were selected as paired stimuli for recording brain waves. Then the factors extracted from the ACF and the cross-correlation function (CCF) of the alpha waves of brain waves were analyzed.

II. METHODOLOGY

A. Subjective preference test

The light source was a 7-mm-diam green LED, set at a distance of 0.6 m from the subject in dark surroundings. The LED stimulus field was spatially uniform and its size corresponds to 0.8 deg of visual angle. Stimulus waveforms were generated by a computer with a 16-bit digital-to-analog converter. The luminance of the stimulus is given by

$$L(t) = L_0[1 + m\cos(2\pi f t)], \qquad (1)$$

where L_0 is mean luminance, m is modulation (relative) amplitude fixed at 1.0, and f is the temporal frequency of the stimulus. Temporal frequency was set at 0.42, 0.63, 1.25, or 2.50 Hz, and mean luminance was set at 7.5, 30, or 120 cd/m^2. The duration of the stimuli was fixed at 5.0 s.
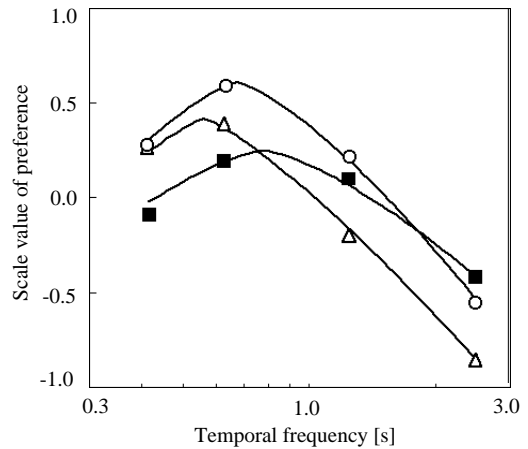

Fig. 1 Scale values of subjective preferences as a function of the temporal frequency. Different symbols indicate different mean luminance. (■): 7.5 cd/m^2, (○): 30 cd/m^2, (△): 120 cd/m^2.

Ten subjects, males, 23 to 25 years old, participated in the experiment. All had normal or corrected-to-normal vision. They dark-adapted for about one minute before all sessions and they were seated in a dark room with a comfortable thermal environment and looked at the LED stimulus. Following the paired-comparison method, each subject compared 66 pairs per session, a total of 10 sessions were conducted for each subject. The interval between the stimuli presentations was 1.0 s, and that between comparison pairs was 4.0 s to allow time for the subjects to respond. The subjects were asked which stimulus they preferred to watch, then they responded by pushing one of two buttons. The scale values of the subjective judgment of each subject, which are regarded as the linear psychological distance between light

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Abstract

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sources, were obtained by applying the law of comparative judgment. The scale values of the subjective judgments of each subject were calculated according to Case V of Thurstone's theory [6]. The model of Case V for all data was reconfirmed by a goodness of fit test [7].

Global scale values of preferences obtained from the 10 subjects are shown in Fig. 1. Effects of temporal frequency and mean luminance on the scale values of preference were examined with all 10 subjects using the two-way analysis of variance (ANOVA). The ANOVA results clearly indicate that temporal frequency and mean luminance are independent of the subjective preference judgments. Moreover the effects of temporal frequency were found to be significant ($p < 0.001$), the effects of mean luminance were not.

B. Recording of EEGs

The same subjects used in the preference tests participated in the recordings of the brain waves. Before the test, each subject was asked to abstain from smoking and drinking of any kind of alcoholic beverage for about 12 hours prior to the test. EEGs were recorded under three conditions: (1) temporal frequency changes and mean luminance fixed; (2) temporal frequency fixed and mean luminance changes; (3) both temporal frequency and mean luminance change. To find a significant effect of subjective preference on an EEG, the most preferred flickering lights and the least preferred flickering lights were selected as a pair stimuli under each condition. According to individual differences of the subjects, the pair stimuli were set for each subject. The subjects watched the most and the least preferred flickering lights alternatively. The interval between pairs was 1.0 s. A series of EEGs wad recorded three times for each subject, and one series consisted of 10 stimuli pairs.

The EEGs from the left and right cerebral scalps were picked up by silver electrodes (7-mm diameter) at points Cz, T3, T4, T5, T6, O1, and O2 (10 - 20 International Electrode Placement System). The reference electrodes were attached to both left and right earlobes. The ground electrode was placed on the forehead. The EEGs were sampled at 100 Hz after passing through a 30-Hz low-pass filter and stored on digital tape for off-line processing. The recorded data were filtered with a digital-bandpass filter with cut-off frequencies of 8 and 13 Hz (alpha-wave ranges).

C. Autocorrelation function (ACF)

As is well known, the autocorrelation function (ACF) provides the same information as the power-density spectrum of a signal. There are four factors [8]. The first is the effective duration of the normalized ACF, τ_e. The second is the energy at the origin of the delay, $\Phi(0)$. The third and fourth factors are represented by the first peak, ϕ_1 and the delay time, τ_1. A normalized ACF can be expressed by

$$\phi(\tau) = \frac{\Phi(\tau)}{\Phi(0)}, \quad (2)$$

where

$$\Phi(\tau) = \frac{1}{2T} \int_{-T}^{+T} \alpha(t)\alpha(t+\tau)\,dt; \quad (3)$$

where 2T is the integral interval, τ is the time delay, and $\alpha(t)$ is the alpha wave of an EEG. Fig. 2 shows the absolute value in the logarithmic form as a function of the delay time. To derive the degree of decay of the ACF, the effective duration, τ_e, defined by the delay τ at which the envelope of the ACF becomes –10 dB (or 0.1; the ten percentile delay), is determined. As shown in Fig. 2, a straight-line regression of the ACF can be drawn using only the initial declining portion 0 dB $> 10 \log |\phi(\tau)| > -5$ dB [3]. In most cases, the envelope decay of the initial part of ACF may be fitted by a straight line. $2T = 2.5$ s was used for our ACF analysis of τ_e and $\Phi(0)$, which is the shortest duration needed to make subjective preference judgments [3,9].
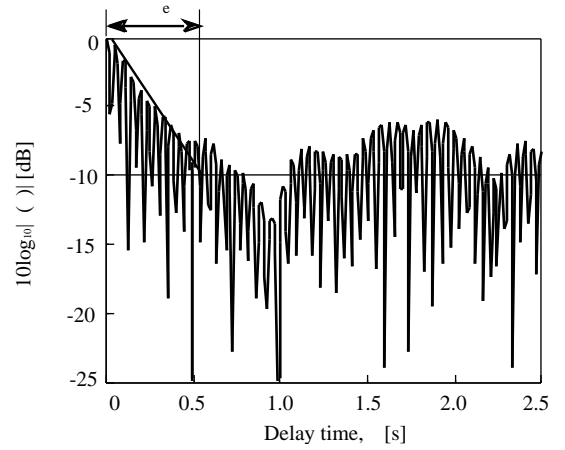

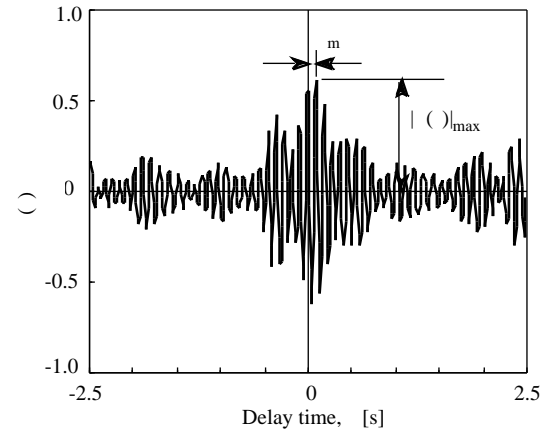Fig. 2 Example of determining the effective duration of ACF (τ_e).

Fig. 3 Definition of $|\phi(\tau)|_{max}$ and τ_m of normalized CCF between the alpha waves obtained from the O1 and those from the rest electrode.

C. Cross-correlation function (CCF)

Let two signals $\alpha_1(t)$ and $\alpha_2(t)$, then the CCF for delay time τ is defined by

$$\Phi_{12}(\tau) = \frac{1}{2T} \int_{-T}^{+T} \alpha_1(t)\alpha_2(t+\tau)\,dt. \quad (4)$$

The normalized CCF is given by

$$\phi_{12}(\tau) = \frac{\Phi_{12}(\tau)}{\sqrt{\Phi_{11}(0)\,\Phi_{22}(0)}}, \quad (5)$$

where $\phi_{11}(0)$ and $\phi_{22}(0)$ are autocorrelation functions of $\phi_1(t)$ and $\phi_2(t)$, respectively, at $\tau = 0$. We calculated the normalized CCF between the alpha waves measured at electrode positions O1 and O2 (reference electrodes) and those from the other electrodes (test electrodes) because O1 and O2 are close to visual area. The same integration interval of the CCF (2.5 s) used in the ACF analysis was used.

An example of a normalized CCF is shown in Fig. 3. Positive lag ($\tau > 0$) means the activity of the reference electrode is delayed. $|\phi(\tau)|_{max}$ was defined as the maximum value of the CCFs in the range of $\tau \geq 0$ and τ_m was defined by as its delay time.

III. RESULTS

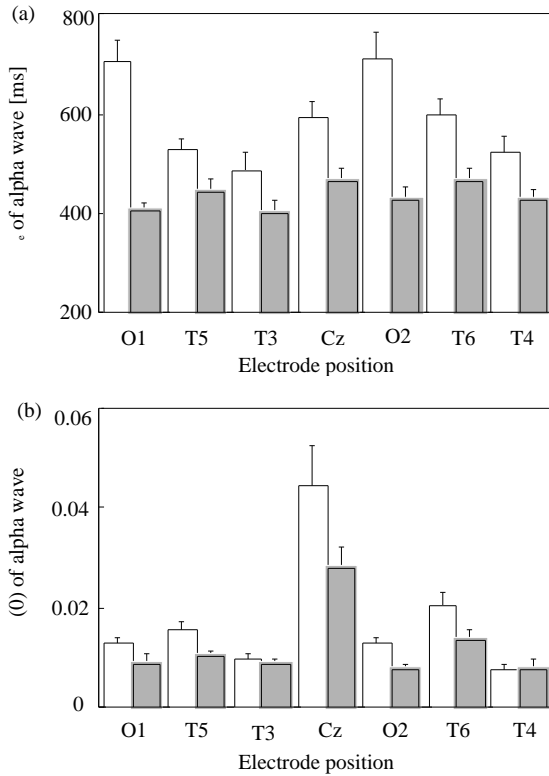### A. Autocorrelation analysis

(a)

(b)

Fig. 4 Calculated (a) τ_e and (b) $\phi(0)$. Error bars represent 95% confidence, white bars show higher preference, and gray bars show lower preference.

When only temporal frequency changes, τ_e and $\phi(0)$ under the most preferred stimuli are larger than those under the least preferred stimuli of all subjects as shown in Figs. 4(a) and (b). This tendency was clear especially in the EEGs from occipital area (O1, O2) (p < 0.001). The values of τ_e do not correlate to the values of $\phi(0)$ (r = 0.19). When both temporal frequency and mean luminance change simultaneously, the values of τ_e and $\phi(0)$ under the most preferred stimuli are larger than those under the least preferred stimuli. There are no clear differences in the factors extracted from the ACF when only mean luminance changes.

Fig. 5 show the ratio of high to low preference in terms of the averaged values of τ_e and $\phi(0)$ when only temporal frequency changes. Remarkable finding that the ratios of τ_e are clearly greater at the occipital area (O1 and O2) than

other area. Also, the ratios of $\phi(0)$ are greater at the occipital area (O1 and O2), posterior temporal area (T5 and T6), and central area (Cz). These results imply that the ratios of τ_e become smaller as the electrode position is shifted from the occipital area to the temporal area.
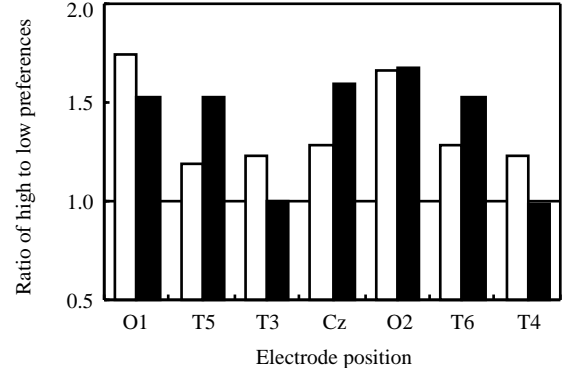
Fig. 5 Ratio of high to low preference in terms of τ_e and $\phi(0)$. White bars show τ_e and black bars show $\phi(0)$.
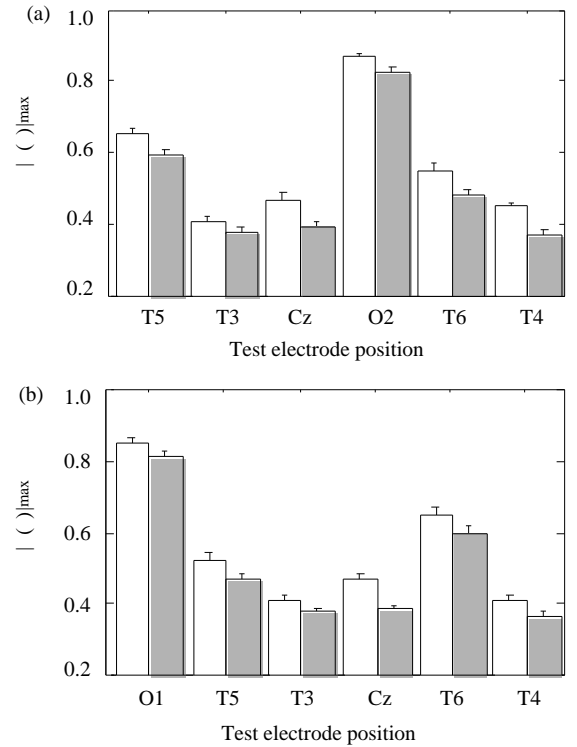
B. Cross-correlation analysis

(a)

(b)

Fig. 6 Calculated $|\phi(\tau)|_{max}$ when (a) reference electrode is O1 and (b) reference electrode is O2. Error bars represent 95% confidence, white bars show higher preference, and gray bars show lower preference.

When only temporal frequency changes, $|\phi(\tau)|_{max}$ under the most preferred stimuli are larger than those under the least preferred stimuli of all subjects as shown in Figs. 6. When both temporal frequency and mean luminance change simultaneously, the values of $|\phi(\tau)|_{max}$ under the most preferred stimuli are larger than those under the least preferred stimuli. There are no clear differences in the values of $|\phi(\tau)|_{max}$ when only mean luminance changes.

As shown in Fig. 6, $|\phi(\tau)|_{max}$ decreases as the distance between reference and test electrode increases. This tendency is also seen when only mean luminance was changed and both temporal frequency and mean luminance were changed. In addition, the delay time of the maximum value of the CCF (τ_m) increases as the distance between reference and test electrode increases as shown in Fig. 7.
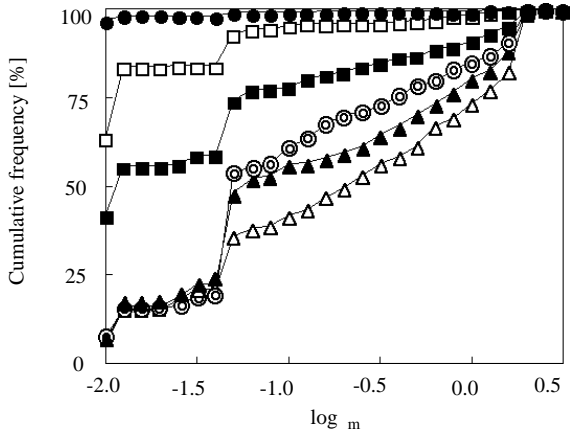

Fig. 7 Cumulative frequency curves of τ_m (logarithmic scale) at the most preferred temporal frequency. Each symbol indicates different test electrode: ($\square$) T5, ($\triangle$) T3, ($\bullet$) O2, ($\blacksquare$) T6, ($\blacktriangle$) T4, and ($\odot$) Cz (Reference electrode is O1).

IV. DISCUSSION

Under the preferred condition of visual stimuli when temporal frequency is changed, alpha waves with a significantly larger τ_e are found as referred that under the less preferred condition, especially at the occipital area. This tendency of τ_e under the preferred condition is also found in previous studies in changing the delay time of a single sound reflection [3], reverberation time of music sound field [4], and noise-burst tempo [5]. The τ_e signifies the degree of similar repetitive features included in alpha waves. The fact that alpha waves have a significantly larger τ_e indicates the brain repeats its rhythm under the preferred condition.

When the delay time of the single reflection [3], the reverberation time [4], of the music sound field, and acoustic tempo [5] are changed, greater values of τ_e at T3 (left hemisphere) than at T4 (right hemisphere) can be seen. Since O1 (left hemisphere) and O2 (right hemisphere) are closely located, the differences between them are unclear when temporal frequency is changed. As shown in Fig. 5, however, a slightly greater value of τ_e at O1 than at O2 can be seen when temporal frequency is changed. A larger value τ_e on the left hemisphere indicates the specialization of the human brain [8], that is, left hemisphere dominance of temporal factors.

Under the preferred condition of visual stimuli when temporal frequency is changed, alpha waves with a significantly larger $|\phi(\tau)|_{max}$ are found as referred that under the less preferred condition. The $|\phi(\tau)|_{max}$ signifies the degree of similar repetitive features included in alpha waves between two electrodes. The fact that alpha waves have a significantly larger $|\phi(\tau)|_{max}$ indicates the brain repeats its rhythm on wider area under the preferred condition.

Principally, two strategies may be followed in electrophysiological studies of mental processes. The first one uses event-related potentials. The relationships between subjective preferences and the auditory evoked potential in terms of the slow vertex responses (SVRs) were investigated [8, 10]. The second approach deals with the analysis of the spontaneous EEG. Numerous studies have reported relationships between EEG-coherences and mental processes [2, 11-12]. Our method in attempting to understand relations between mental processes, i.e., subjective preference and brain electrical activity, follows the second approach by applying the ACF and the CCF analyses. Since some applications of the ACF indicate the effectiveness as a additional tool in gaining further understanding of EEG dynamics [3-5], it is meaningful to introduce ACF and CCF for EEG analysis as well as coherence analysis.

V. CONCLUSION

Under changing temporal frequency, the preferred stimulus has a significant larger τ_e than that of the least preferred stimulus, especially at occipital area O1 and O2, and a significant larger $\phi(0)$ at occipital area O1 and O2, posterior temporal area T5 and T6, and central area Cz, and a significant larger $|\phi(\tau)|_{max}$.

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